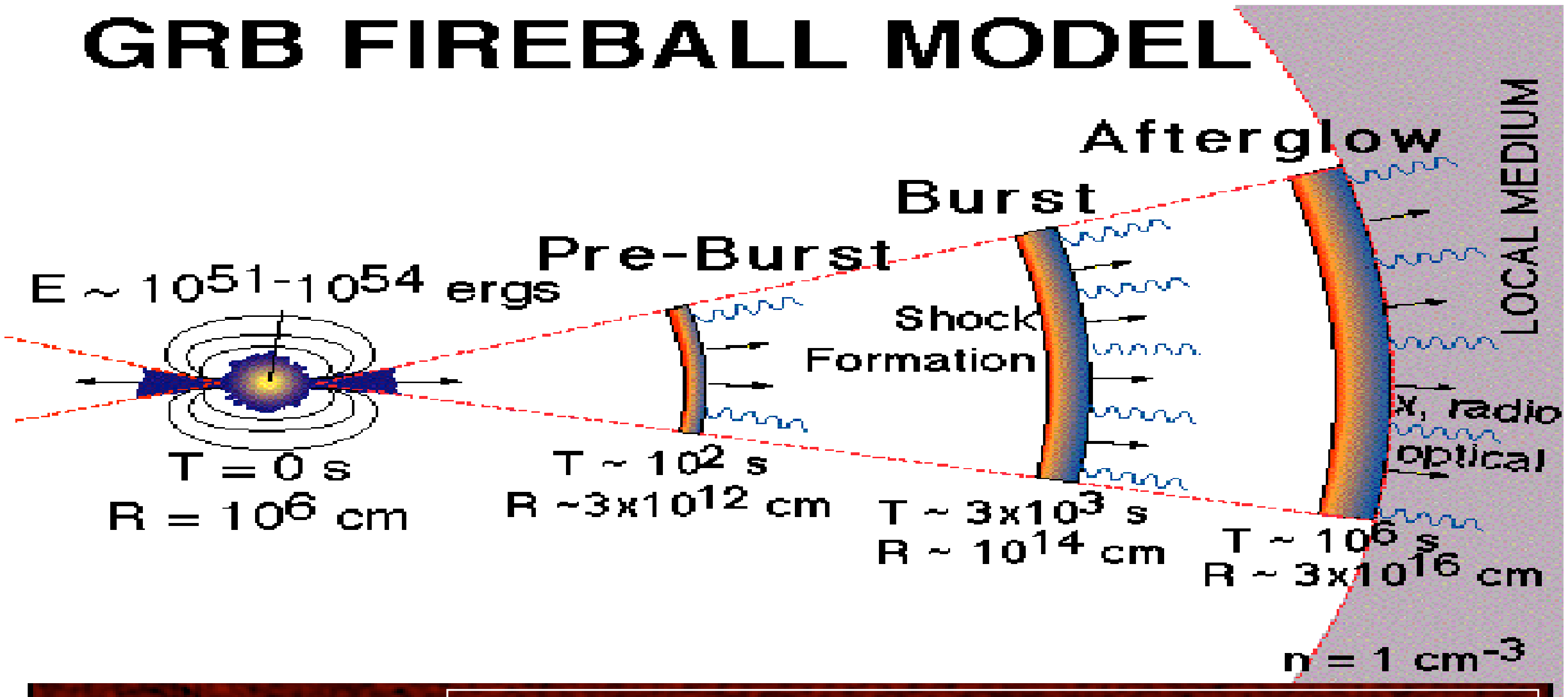
Towards a complete theory of GRBs

Arnon Dar & Alvaro De Rujula

Vulcano Workshop, May 25, 2006

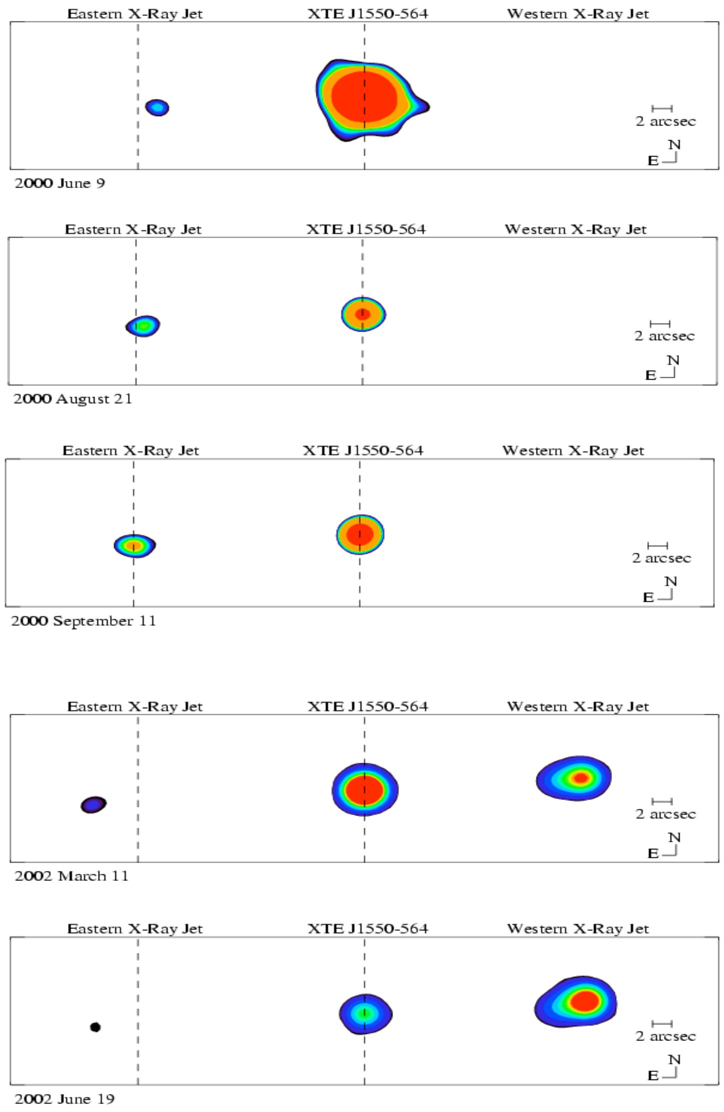


GRB FIREBALL MODEL
Afterglow
Burst
Pre-Burst
E ~ 10^{51}-10^{54} ergs
Shock
Formation
LOCAL MEDIUM
X, radio
optical
T = 0 s
R = 10^6 cm
T ~ 10^2 s
R ~3×10^{12} cm
T ~ 3×10^3 s
R ~ 10^{14} cm
T ~ 10^6 s
R ~ 3×10^{16} cm
n = 1 cm^{-3}

Astrophysical jets are not conical shells
Quasar 3C175
Quasar 3C175
VLA 6cm image (c) NRAO 1996

Bipolar jets of cannonballs of ordinary matter are ejected by compact objects following mass accretion episodes

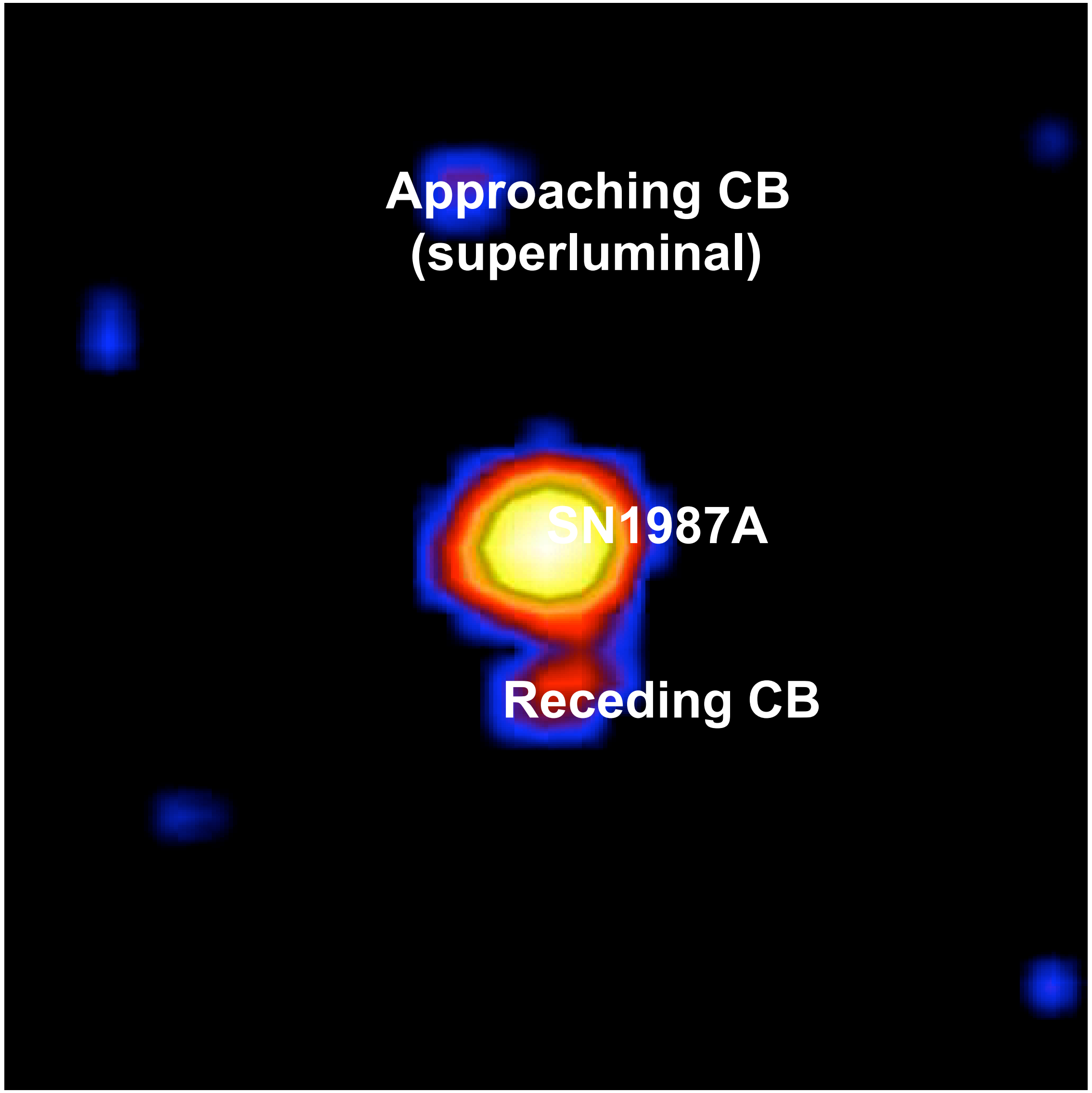
Deceleration of CBs fired by the Microquasar XTE J1550-564 in August 1998 (Corbel et al. 2003)



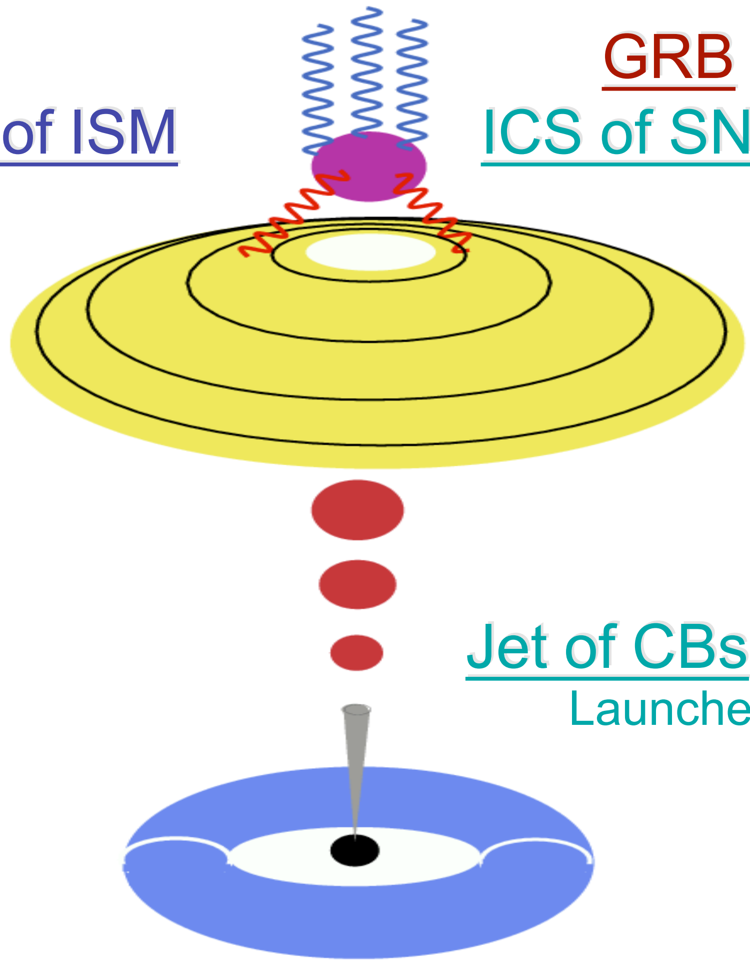
flare up of a CB by collision with a density bump?

A1987 The two CBs fired by SN

Nisenson & Papaliolios
ApJ 518, L29 (1999)



The Cannonball (CB) model of GRBs/XRFs

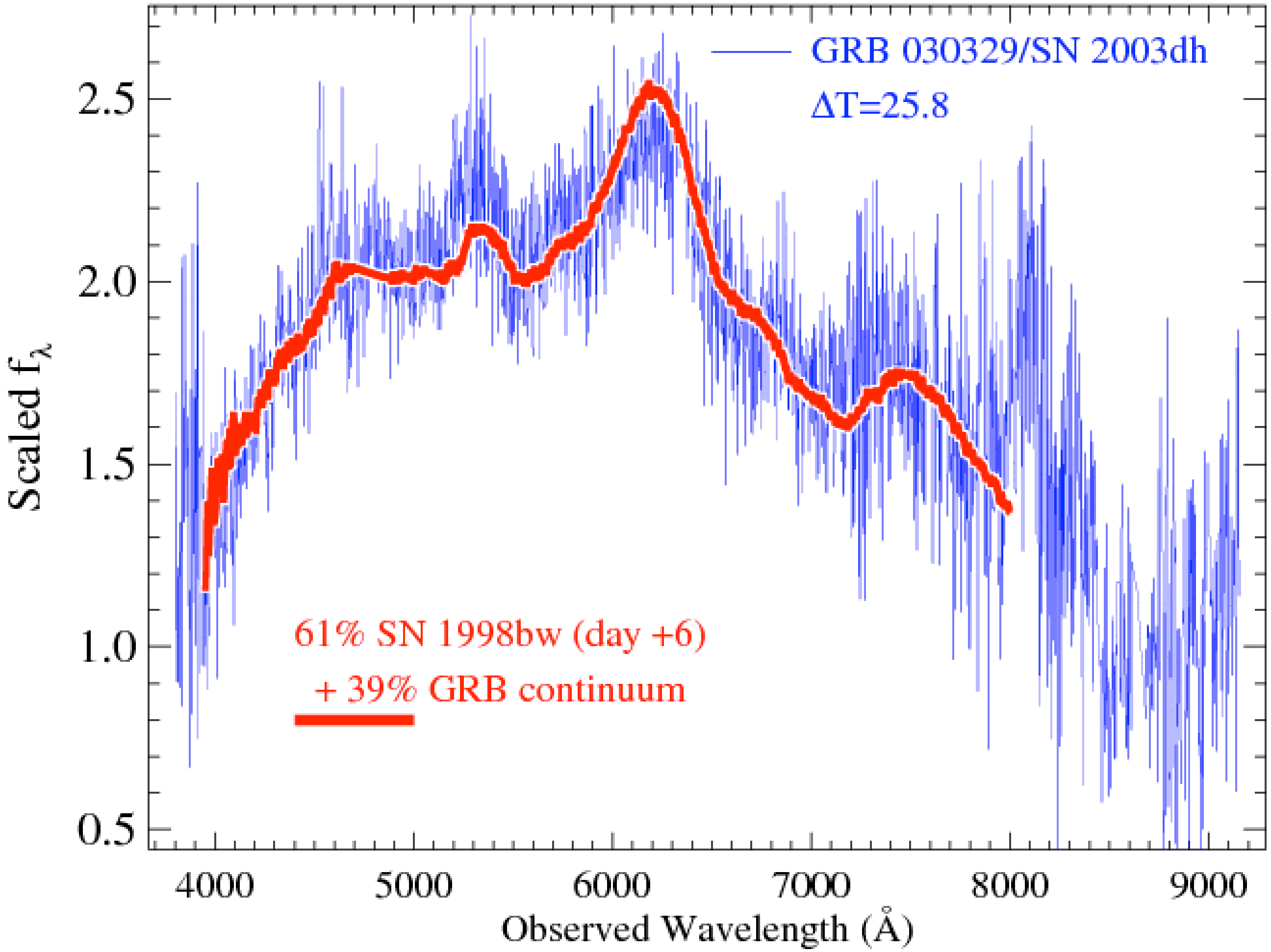


CB Model of GRBs, CRs,

Bipolar jets fired in mass accretion episodes (Shaviv-Dar 1995) of fallback matter on compact central object (De Rujula 1987) in SNe

The CB model was based on a proposed **SN-GRB association** (Dar et al. 1992, [but, Wooseley 1993: (failed SN) - GRB association], Shaviv & Dar 1995, Dar & Plaga 1999, Dar & De Rujula 2000. Conclusive evidence from 1997-2003 observations claimed in many DD, DDD publications was ignored/ encountered skepticisim until SN2003dh akin to SN1998bw was discovered in the afterglow of GRB030329 on the predicted day by DDD (astro-ph/0304106)

– 109 –



Radiation from Relativistic CBs

Acceleration of Particles

Beaming of Emissions

Confinement of CBs

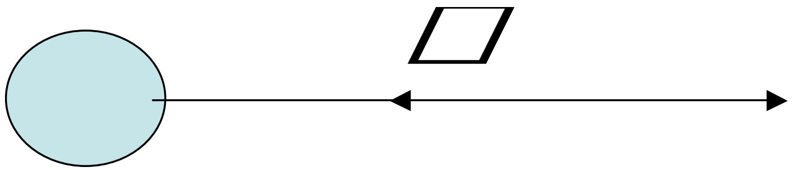
Deceleration of CBs

Emission of Radiation

A,B,C,D discussed in detail in De Rujula's talk

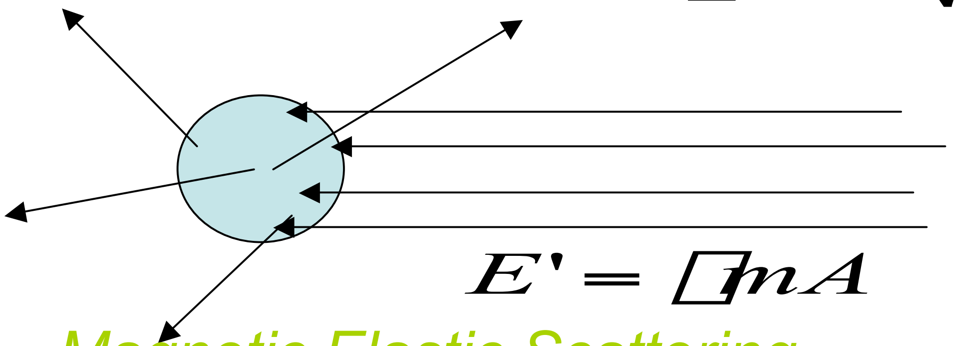
Fermi Acceleration By Relativistic Cannonball

CB



Lab Frame

$$\gamma = 1/\sqrt{1 - \beta^2}$$



$$E' = \gamma m A$$

Magnetic Elastic Scattering

CB's Rest Frame

$$E = \gamma E'(1 + \beta^2 \cdot \cos\theta')$$

$$E_{\max} \approx (2\gamma^2 - 1) A \cdot m$$

$$\frac{dn}{dE} \approx \frac{n}{(2\gamma^2 - 1) A \cdot m} \Theta(E - (2\gamma^2 - 1) A \cdot m)$$

(Atter Isotropization in CB)

Relativistic Beaming

$$\cos\theta' = \frac{\cos\theta - \beta}{1 - \beta\cos\theta}$$

$$\frac{dn}{d\Omega} = \frac{dn}{d\Omega'}\frac{d\cos\theta'}{d\cos\theta} = \frac{dn}{d\Omega'}\delta^2$$

$$\delta = \frac{1}{\gamma(1 - \beta\cos\theta)} \approx \frac{2\gamma}{1+\gamma^2\theta^2} \quad \text{for} \quad \gamma^2 >> 1,\ \theta^2 << 1$$

$$\frac{dn}{d\Omega} \approx \frac{n}{4\pi}\delta^2 \approx \frac{n}{\pi}\left(\frac{\gamma}{1+\gamma^2\theta^2}\right)^2 \approx \begin{cases} n\gamma^2/\pi & \text{for} \quad \gamma^2\theta^2 << 1 \\ n/\pi\gamma^2\theta^4 & \text{for} \quad \gamma^2\theta^2 >> 1 \end{cases}$$

Particles emitted isotropically in the CBs' rest frame are beamed in the lab frame into a narrow cone of an opening angle:

$$\boxed{\theta_b \approx 1/\gamma}$$

Deceleration of CBs

$$d(M\gamma) = 0 \Rightarrow \; M d\gamma = -\gamma\, dM$$

$$M d\gamma = -\, dN\, \gamma\, m_p = -\pi R^2 \gamma\, n\, dx = \frac{-\pi R^2 n \gamma^2 \beta c\, dt}{(1+z)}$$

e.g. for constant R

$$\Rightarrow \left(\frac{\gamma_0}{\gamma}\right)^4 + 2\gamma_0^2\theta^2 \left(\frac{\gamma_0}{\gamma}\right)^2 = \frac{t}{t_0} + 2\gamma_0^2\theta^2 + 1$$

$$where: t_0 = \frac{(1+z)N_b}{8cn\pi R^2\gamma_0^3} \approx \frac{(1+z)N_{50}}{n_{-3}R_{14}^2\gamma_3^3} 1.3\cdot 10^4 \sec$$

$\gamma(t)$ **changes slowly with time until** $t \approx t_{break} \approx (2\gamma_0^2\theta^2 + 1)t_0$

The power-law dependence of F_ν on ν produces a kinematical break which depends on the viewing angle

Dominant Emission Mechanisms

time ↓

ICS of SN Light ⟷ GRB

Brem+Line Cooling → Early time AG

Synchrotron Radiation → Late time AG

Evidence:

GRB- pulse shape, pulse duration, energy dependence, spectrum, peak energy, spectral evolution, fluence, polarization, correlations

Early AG- spectrum, light curve

Late AG- spectrum, light curve

Table 1 Main Assumptions of the FB and CB Models of Long Duration GRBs

Property	Fireball Model	Cannonball Model
Progenitors	Massive Stars	Massive Stars, Compact Binaries
Event	Hypernova,	CC Supernova, AIC of wd/n* in a binary
Environment	Progenitor Wind, ISM	SN+Pre SN ejecta, SB
Remnant	bh	bh, or sq*, or n*
Ejecta	Baryon poor e^+e^- Shells	Ordinary-Matter Plasmoids
Geometry	Conical Shells	Cannonballs (CBs)
Ejection time	During Core Collapse	After Fall-Back of Ejecta
Radiation	Synchrotron from Colliding Shells	ICS of SN Glory by CBs
Lorentz Factor	$\Gamma > 300$	$\Gamma \sim 1000$
Viewing Angle	$\theta < \theta_j$	$\theta \sim 1/\Gamma$

Abbreviations: bh = black hole; n* = neutron star; sq* = strange quark star; wd = white dwarf; SN = supernova; SB = Superbubble; AIC = accretion induced collapse; ICS = inverse Compton scattering; θ_j = opening angle of the conical jet (relative to its axis).

Table 2 The FB and CB Model assumptions for AGs of Long Duration GRBs

Property	Fireball Model	Cannonball Model
Origin	FB Blast Wave in ISM	CB Interaction with ISM
Ejecta	Conical e^+e^- Shells	Jet of Ordinary-Matter Plasmoids
External Medium	Progenitor Wind, ISM	Progenitor Wind → SB → ISM
Early AG	SR from Reverse Shock	Brem. and Line Cooling
Late AG	SR from Shocked ISM	SR from CBs and scattered ISM
Lightcurve Break	Jet Expansion+Deceleration	Off-Axis Viewing of Decelerating CBs
Early Flares	Extended Central Activity	Late Accretion Episodes
Late Flares	Extended Central Activity	Encounter with Density Bumps
Dark Bursts	Circumburst Absorption	Circumburst Absorption

Abbreviations: SR = Synchrotron Radiation; Brem. = Bremsstrahlung

Table 3 Comparison between Falsifiable Predictions of the FB and CB Models and Observational Data on Long GRBs.

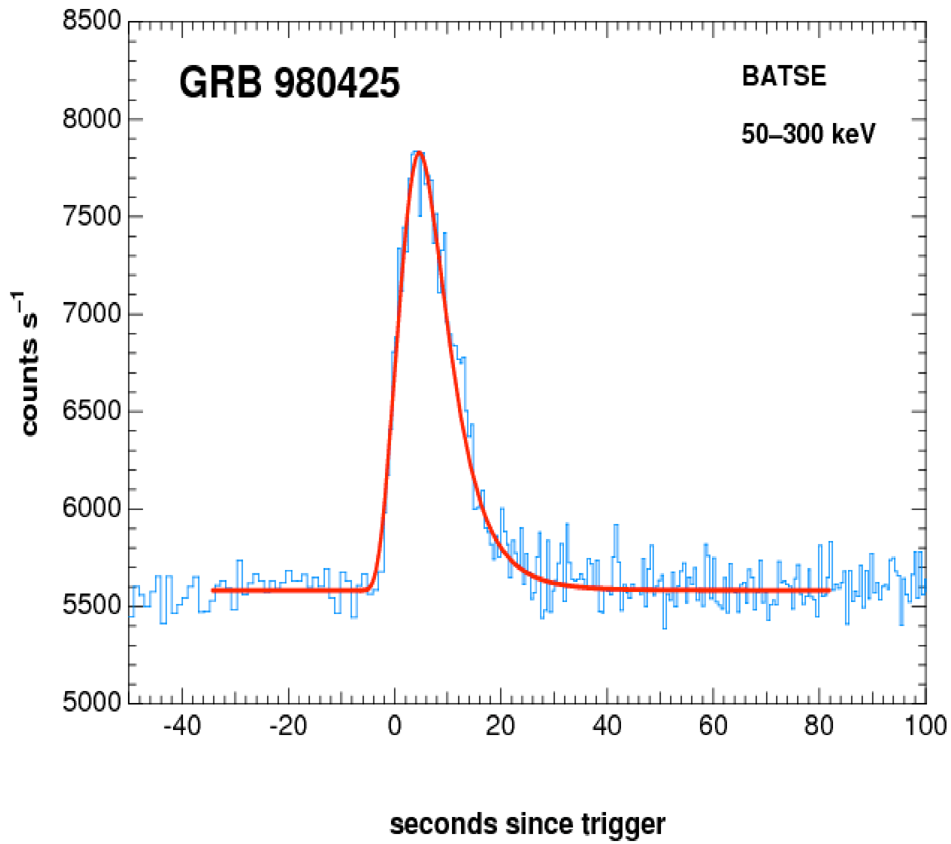
Property	Fireball Model	Cannonball Model	Observations
"Peak" γ-Ray Energy	NP	Eq. (1)	$\sim$ 250 keV
Typical Duration (T_{90})	NP	NP	30s
Mean No of Pulses (n_p)	NP	NP	~ 6
Pulse Shape	FP	Eq.7 "FRED"	"FRED"
"Isotropic Energy"/Pulse	NP	$0.8 \times 10^{53}\, \delta_3^3$ ergs	$10^{48} - 10^{54}$ ergs
FWHM of Pulses	$(1+z)\, R/2\, c\gamma^2$	$\sim 0.5\,(1+z)/\delta_3$ s	1/2-200 s
Pulse Spectrum	Broken PL	Thermal Brem. + PL Tail	"Band" Spectrum
Pulse Spectral Evolution	NP	Eq. 6	Hard to Soft
Scintillations	NP	NP	Debated
Polarization	NP	$2\,\theta^2\,\gamma^2/(1+\theta^4\,\gamma^4)$	> 50% (3 GRBs)
Correlations (Pulses):			
$(1+z)\, E_p(E_\gamma^{iso})$	NP	$\sim [E_\gamma^{iso}]^{1/3-1/2}$	$\sim [E_\gamma^{iso}]^{0.46\pm 0.13}$
FWHM(E_γ)	$\sim E_\gamma^{-1/2}$	$\sim E_\gamma^{-1/2}$	$\sim E_\gamma^{-1/2}$
Rise-Time/FWHM	NP	~ 0.27	~ 0.30

Abbreviations: NP=Not Predicted; FP=Failed Prediction; PL=Power Law; FRED=Fast Rise Exponential Decay; $\delta = \delta_3 \times 10^3$ (Doppler Factor).

Pulse Shape

$$\frac{dN}{dt} \quad \exp\left[-\left(\frac{t_1}{t}\right)^m\right]\left[1-\exp\left[-\left(\frac{t_2}{t}\right)^n\right]\right]$$

$n \approx m \approx 2; \quad \propto \quad n_{\square} \quad 1/r^2$



Rise-time versus FWHM of single pulses

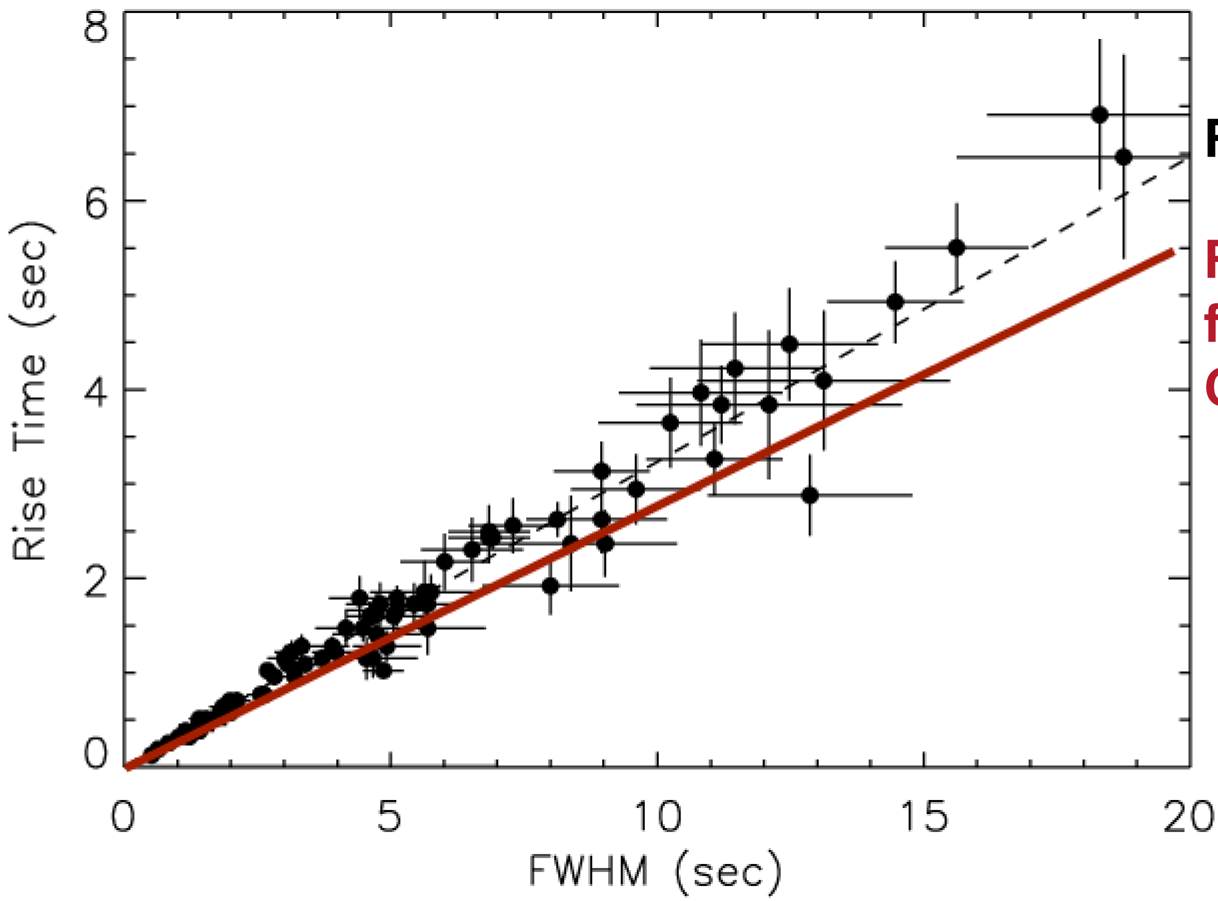


Fig. 11.— Rise-time from half-maximum to maximum versus full width at half-maximum of an ensemble of GRB single pulses (Kocevski et al. 2003). The data are from pulses of bright BATSE GRBs, the theoretical prediction (the continuous line) is from the naive pulse shape of Eq. (37). The dotted line is the best linear fit.

GRB Spectrum

For ICS of thin thermal bremstrahlung:

$$\frac{dN_\gamma}{dE} = a\left(\frac{E}{T_{eff}}\right)^{-\alpha} e^{-E/T_{eff}} + b\left(1 - e^{-E/T_{eff}}\right)\left(\frac{E}{T_{eff}}\right)^{-\beta}$$

$$T_{eff} = \delta T/(1+z)$$

$$\alpha \sim 1, \quad \beta \sim 2.2$$

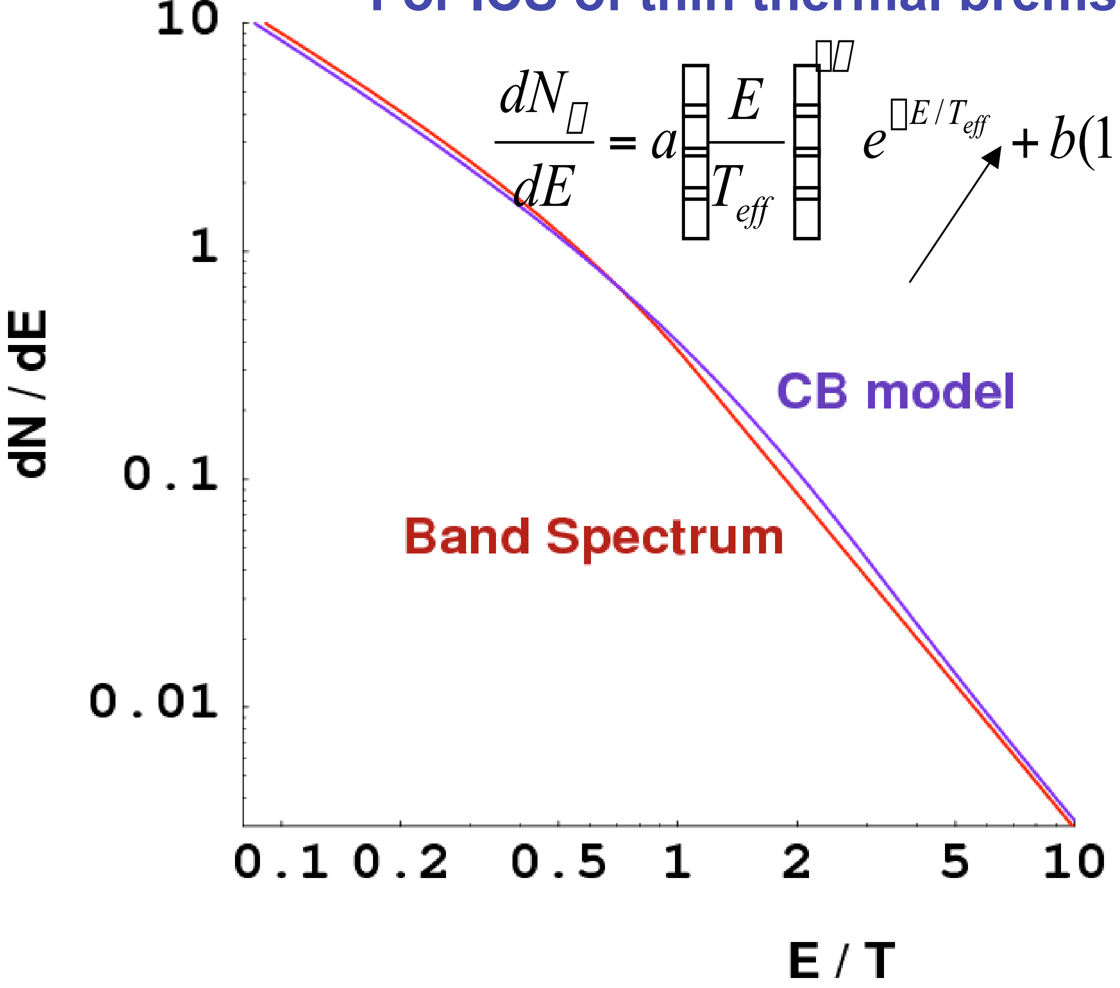


Fig. 12.— Two shapes of GRB spectra, the number of photons per energy interval dN/dE. One is the prediction of the CB model, Eq. (47). The other is the successful phenomenological Band spectrum of Eq. (48) (Band et al. 1993); T stands for the bend energy in the Band's case. Considering that the prediction is based exclusively on first principles, the agreement is rather satisfying.

Peak Energy

For ICS of SN light (T~1 eV):

$$E_p \square \square\square T/(1+z)$$

From SWIFT: <z> =2.75

From CB model fits of AGs: $<\square>\square<\square>\square 10^3$

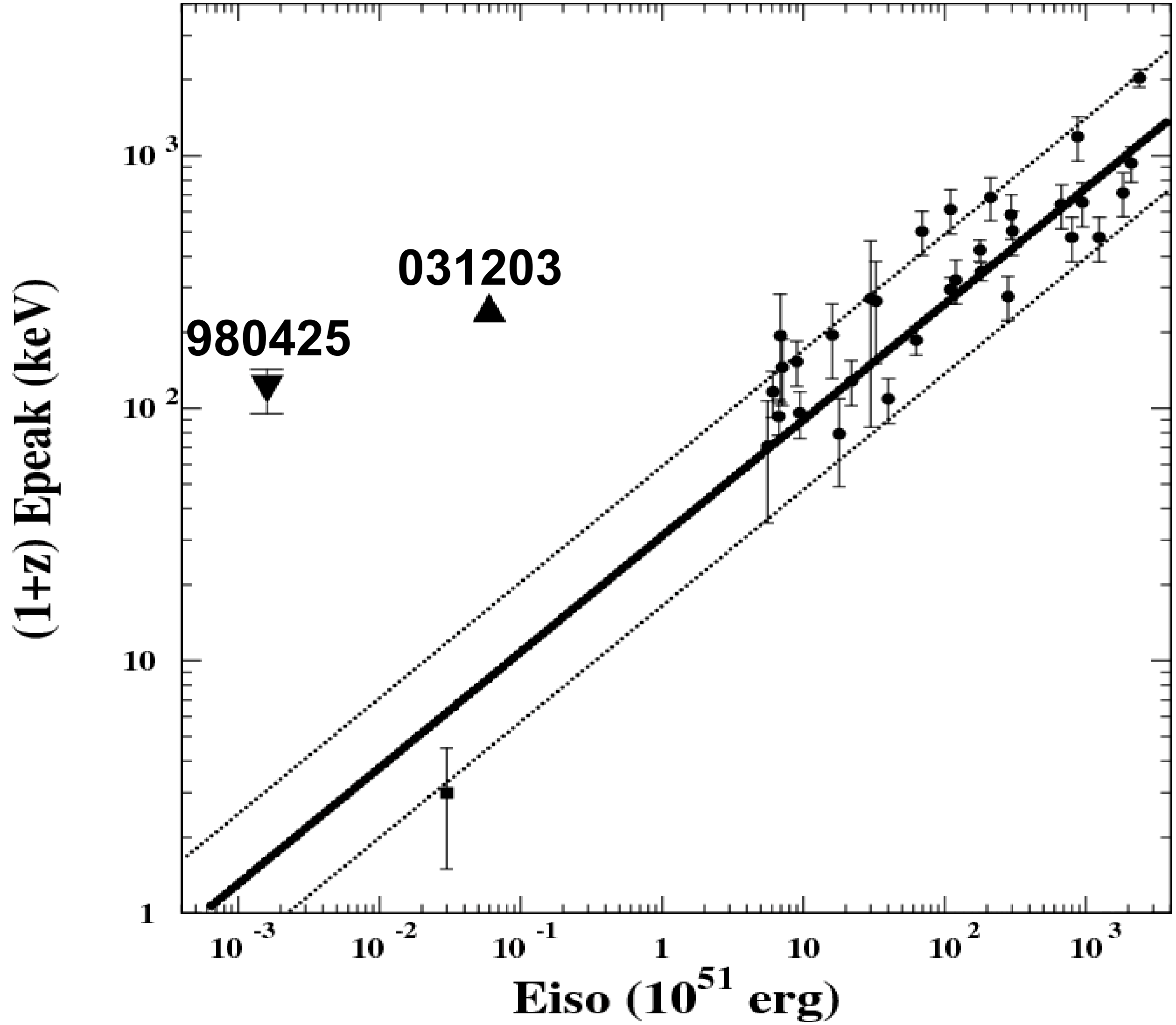
$$\square \quad \boxed{<E_p>\square 265 keV}$$

$$E_{\square}^{iso} = \square^3 E_{\square}^{'}(RF)$$

$$\square \quad (1+z)E_p \quad \left\{ \begin{array}{ll} 1.0\left[E_{\square}^{iso}\right]^{1/3}, & \square^2\square^2 >> 1 \\ 0.5\left[E_{\square}^{iso}\right]^{1/2}, & \square^2\square^2 << 1 \end{array} \right.$$

Correlation between peak energy and total ''isotropic'' energy

The correlation discovered by Amati et al. 2003
was predicted by the CB model (DD 2000)

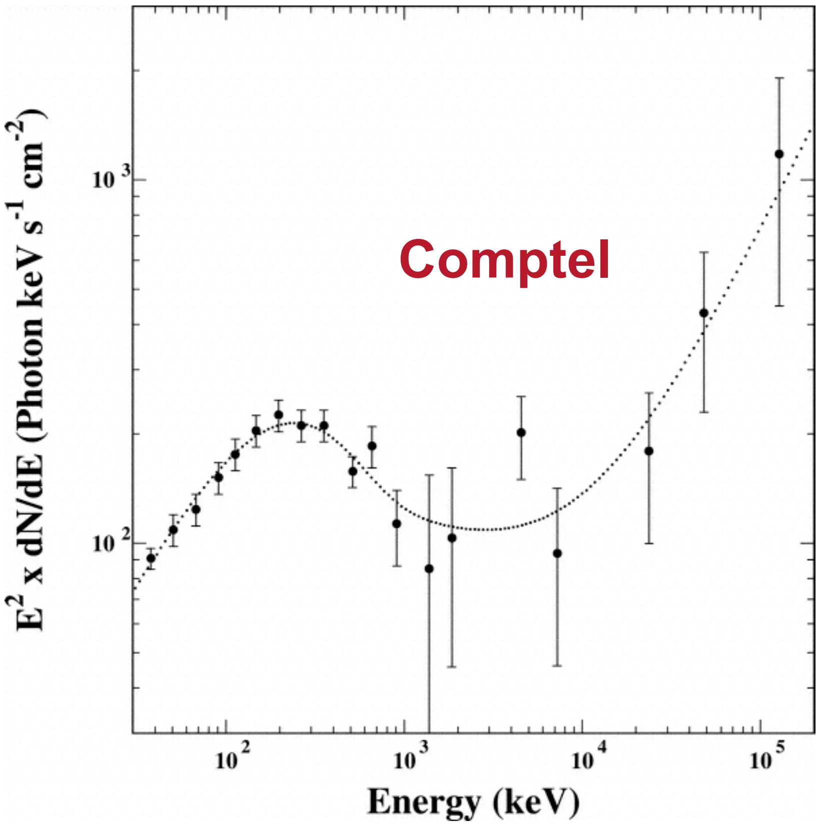


$$\left(E_{\gamma}^{iso}\right)^{0.46\pm.05}$$

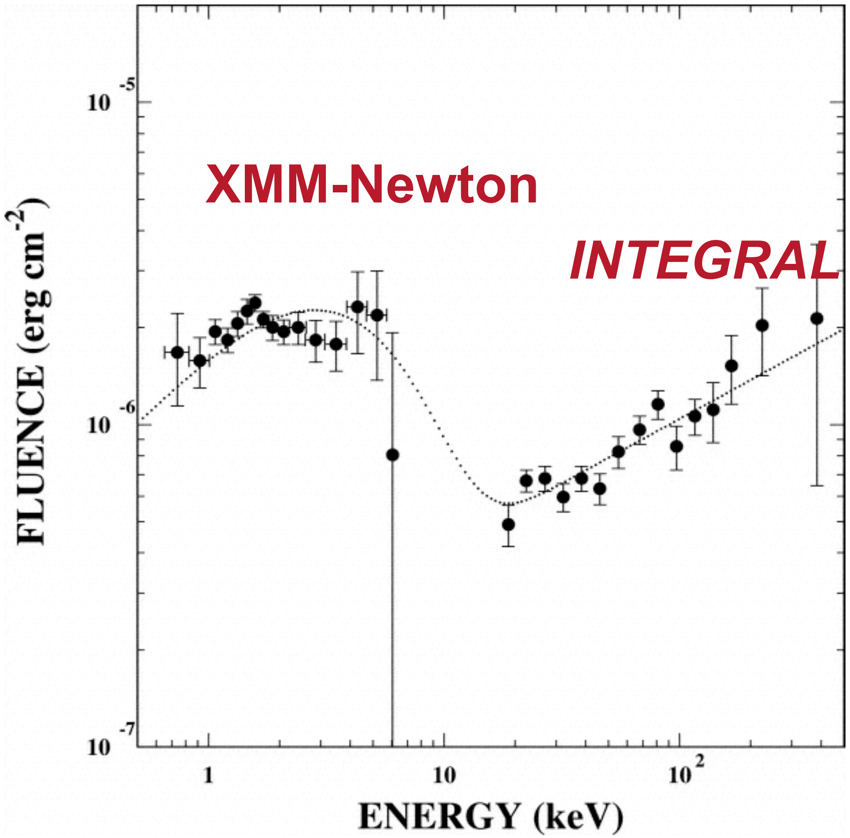
Double peak spectral energy flux (analogous to blazars ?)

by ICS of CBs' plasma electrons + CB accelerated electrons

GRB 941017



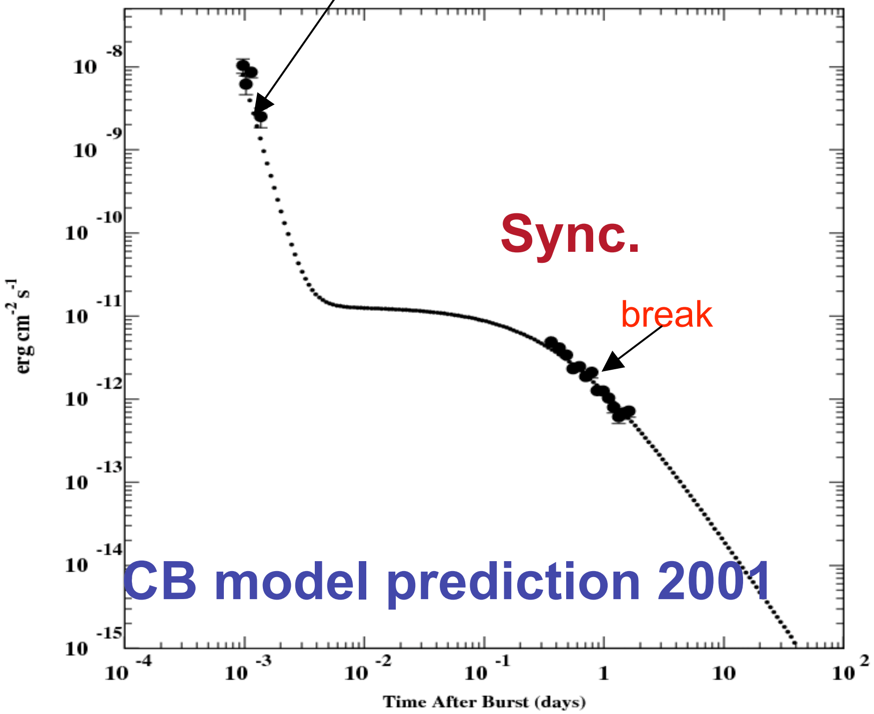
GRB 031203



X-ray afterglow

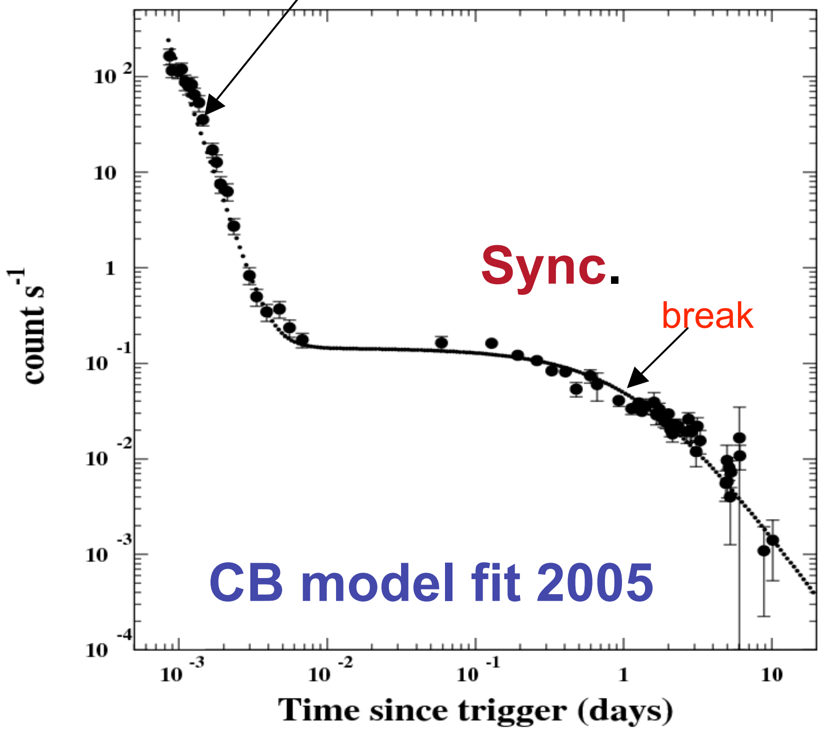
BeppoSAX: GRB 990510
(Pian et al. 2001)

Brem +line cooling



SWIFT: GRB 050315
(Vaughan et al. 2005)

Brem +line cooling

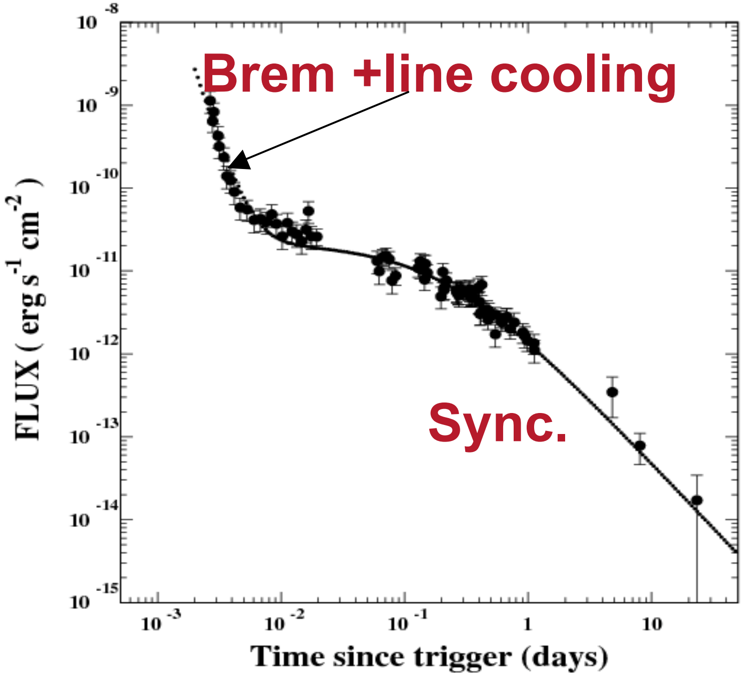


Flares:

Late accretion episodes on the compact central object ?
Encounters with density bumps?

– 10 –

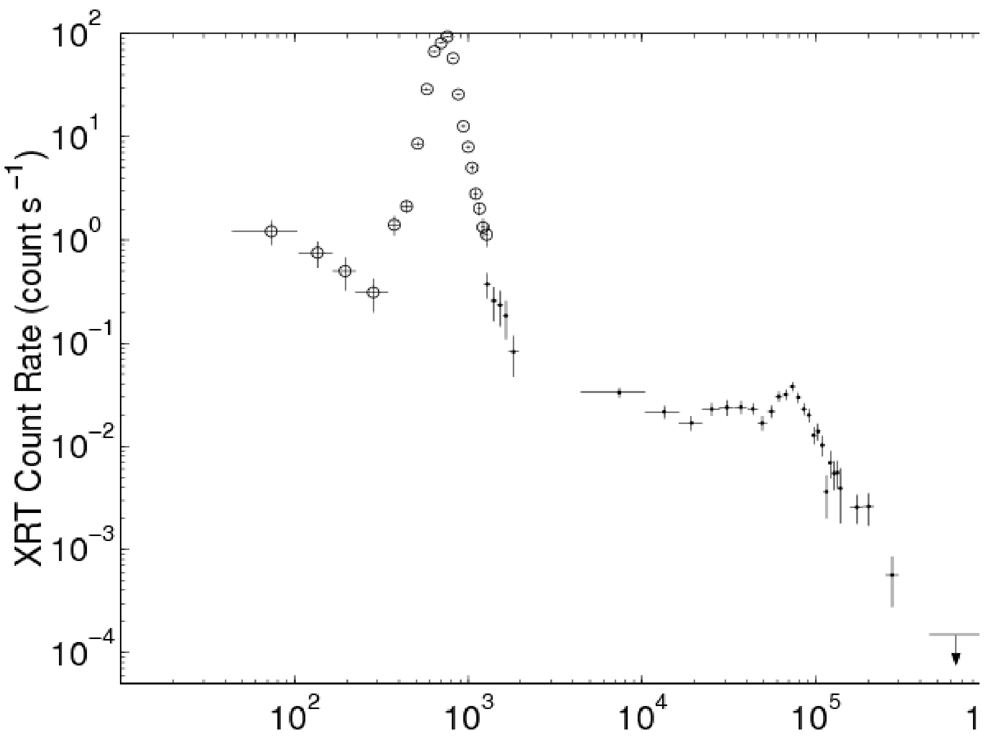
Noisy X-ray Afterglow GRB 050319



g. 2.— Comparison between the X-ray afterglow (0.2–10 keV) of GRB 050319

– 7 –

Flares in the X-RAY afterglow GRB 050502B



GRB 030329
Optical flares due to density jumps?
Data: Lipkin et al. 2004
Theory: CB Model (DDD)

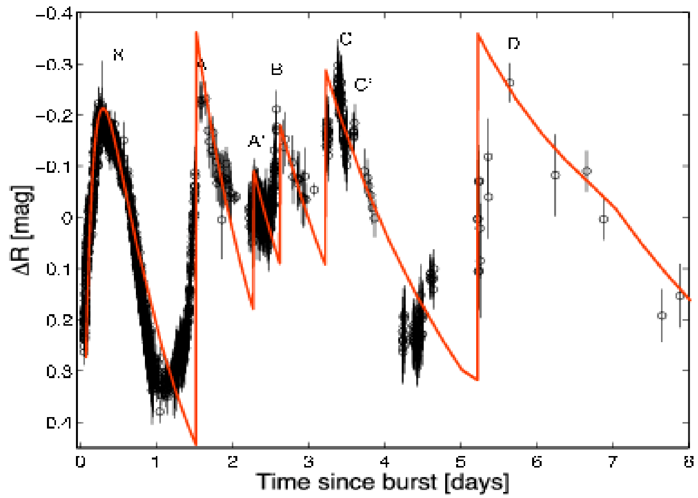


Fig. 3.— Comparison between the R-band AG of GRB 030329, shown as "residua" ΔR of the data (black points and circles) relative to a broken power law of index $-\alpha$ jumping from ~ 1.1 to ~ 2 at $t \sim 5$ days (Lipkin et al. 2004), and the residua, relative to the same broken power law, calculated from the CB model (red line) for the input density profile shown in Fig. 4. The ℵ feature is a prediction (Dado et al. 2004b).

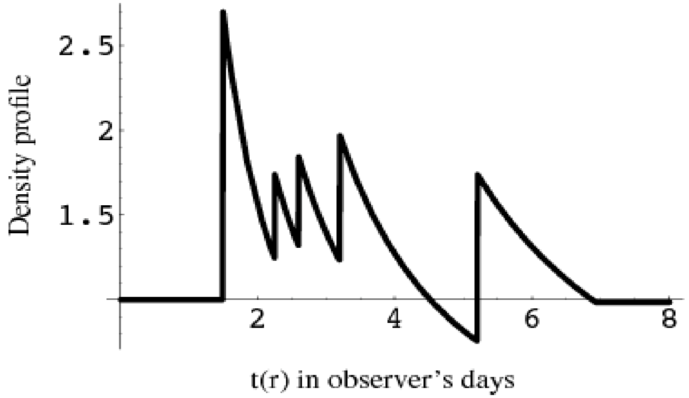
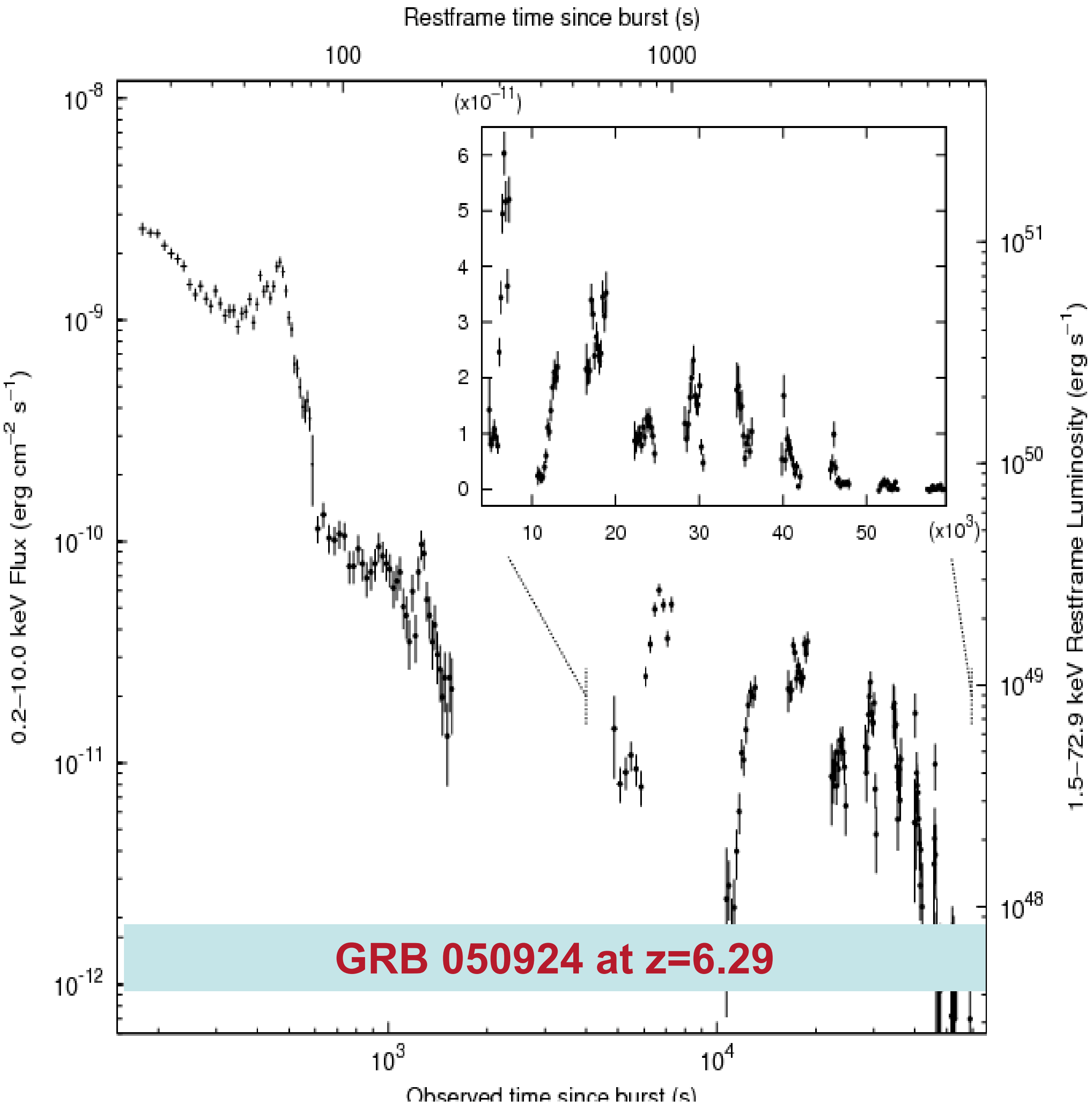


Fig. 4.— The density profile of the CB-model fit to the R-band AG of GRB 030329 (relative to a smooth ISM density —a constant plus a "wind" contribution decreasing as $1/r^2$). The density is $n = \Sigma_j n_j\,(r_j/r)^2\,\Theta(r - r_j)$, with Θ Heaviside's function.



Restframe time since burst (s)
100
1000
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0.2–10.0 keV Flux (erg cm^{-2} s^{-1})
10^{51}
10^{50}
10^{49}
10^{48}
1.5–72.9 keV Restframe Luminosity (erg s^{-1})
(x10^{-11})
6
5
4
3
2
1
0
10
20
30
40
50
(x10^{3})
10^{3}
10^{4}
Observed time since burst (s)
GRB 050924 at z=6.29

FM: Achromatic break in AG of conical jets when $\Gamma(t) \sim 1/\theta_{jet}$

$$\boxed{\theta_{jet} \approx 5^{o}\, t_{j,d}^{3/8} E_{53}^{-1/8} n_e^{1/8} (\eta / 0.2)^{1/8} [(1+z)/2]^{3/8}}$$

and $$\boxed{E_{\gamma} = 2\pi E_{\gamma}^{iso} (1 - \cos\theta_{jet}) \approx \pi\theta_{jet}^{2} E_{\gamma}^{iso}}$$

but, light-curve breaks in Swift GRB afterglows are chromatic

2 *Panaitescu et al.*

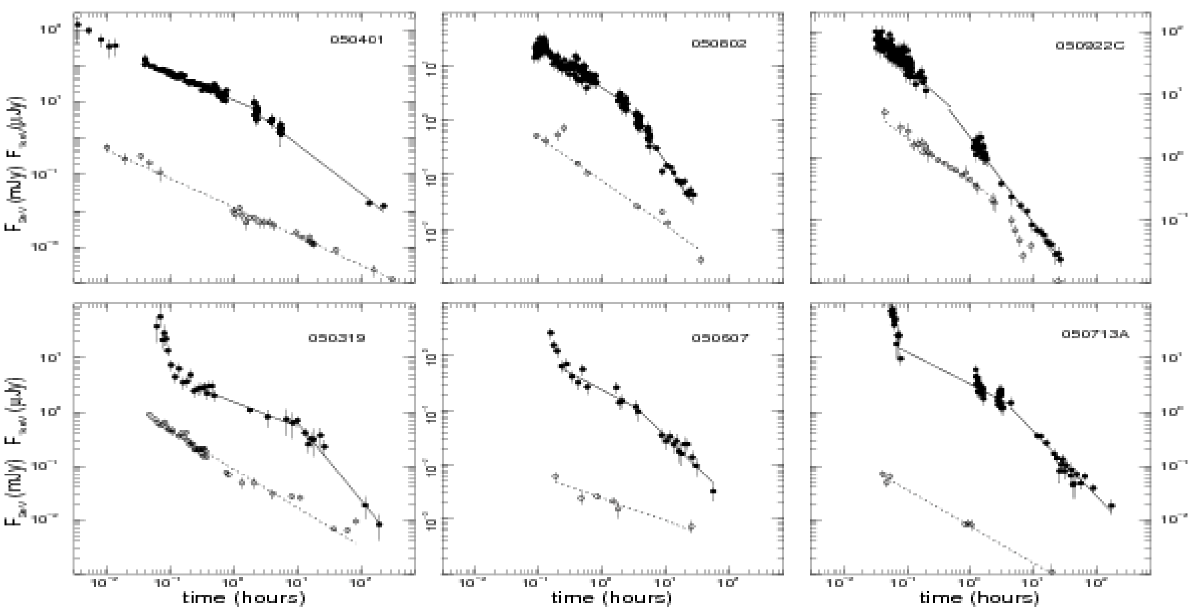


Figure 1. Light-curves of six Swift GRB afterglows showing a chromatic X-ray break which is not seen in the optical at the same time. Optical data are shown with open symbols and are fit with a power-law decay (dotted lines). X-ray data are shown with filled symbols are fit with a broken power-law (solid lines). Optical measurements are from Data are from Woźniak et al. (2005), GCNs 3120 (T. Yoshioka), 3124/3140 (D. Sharpov) (050319); De Pasquale et al. (2006), Watson et al. (2006), Rykoff et al. (2005) (050401); GCNs 3531 & 3540 (J. Rhoads) (050607); Guetta et al. (2006) (050713A); GCNs 3739/3745 (K. McGowan), 3744 (E. Pavlenko), 3765 (V. Testa) (050802); GCNs 4012 (E. Rykoff), 4015 (P. Jakobsson), 4016 (E. Ofek), 4023 (D. Durig), 4026 (T. Henych), 4041 (S. Hunsberger), 4046 (S. Covino), 4048 (M. Andreev), 4040 (J. Fynbo), 4095 (W. Li) (050922C).

Synchrotron Afterglow from Decelerating CBs

$$F_\nu \propto n R^2 [\gamma(t)]^{3\alpha-1} [\delta(t)]^{3+\alpha} \nu^{-\alpha}$$

$$\alpha \approx 0.5 \rightarrow 1.1 \quad \text{when} \quad \nu<\nu_b \rightarrow \nu>\nu_b$$

Deceleration break:

$$\left(\frac{\gamma}{\gamma_0}\right)^4 + 2\theta^2\left(\frac{\gamma}{\gamma_0}\right)^2 = \frac{t}{t_0} + 2\gamma_0^2\theta^2 + 1$$

$$t_0 = \frac{(1+z)N_b}{8cn\pi R^2\gamma_0^3} \approx \frac{(1+z)N_{50}}{n_{-3}R_{14}^2\gamma_3^3} 1.3\cdot 10^4 \text{ sec}$$

$$\Longrightarrow \quad t_{break} \approx (2\gamma_0^2\theta^2+1)t_0 \quad \Longleftarrow$$

XRFs=GRBs with larger viewing angles have later breaks

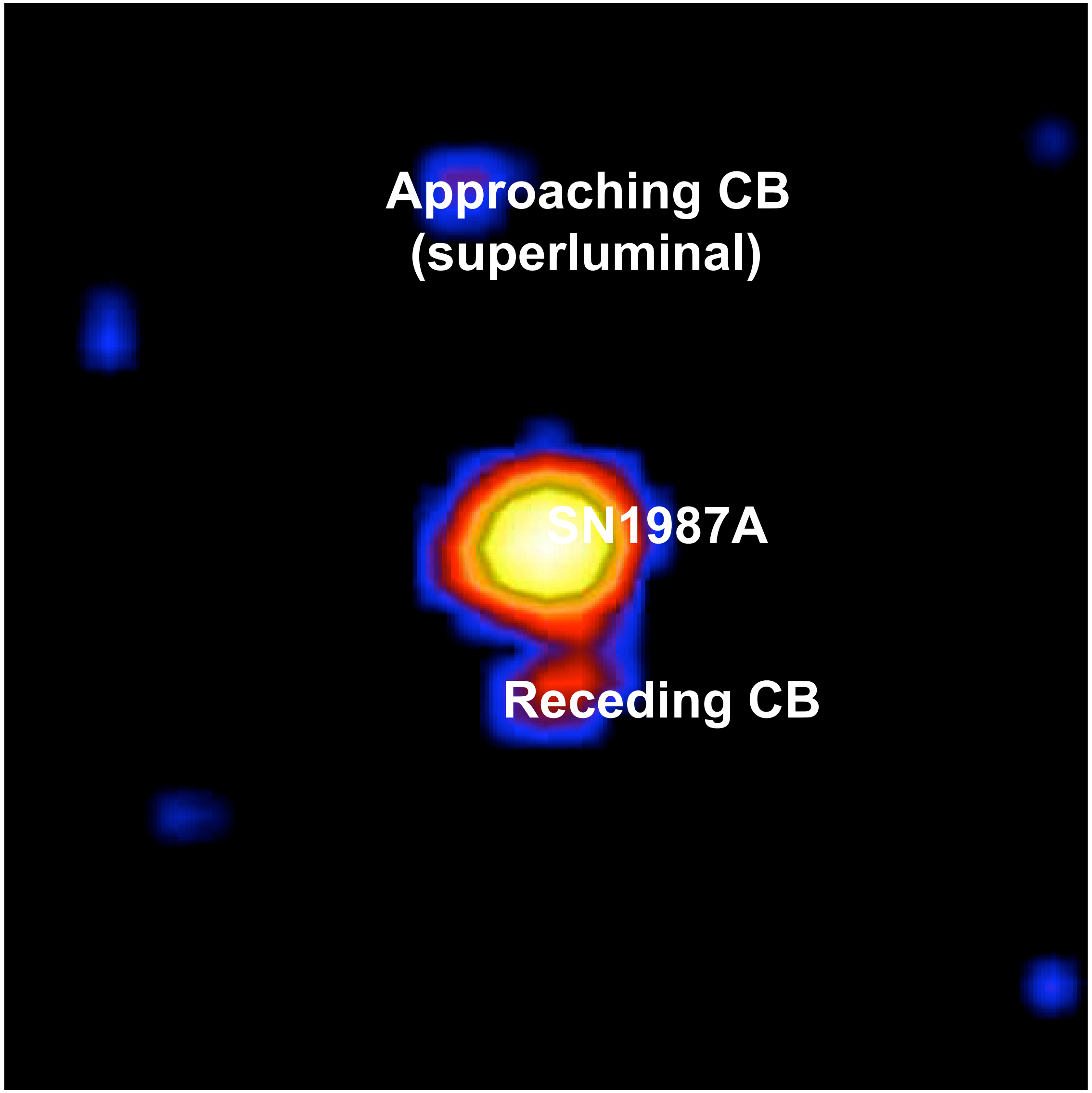
The Cannonball Model of GRBs/XRFs/SHBs

Inverse Compton Scattering of glory photons or ambient light by highly relativistic jets of plasmoids (cannonballs) of ordinary matter ejected in mass accretion episodes on compact central objects in:

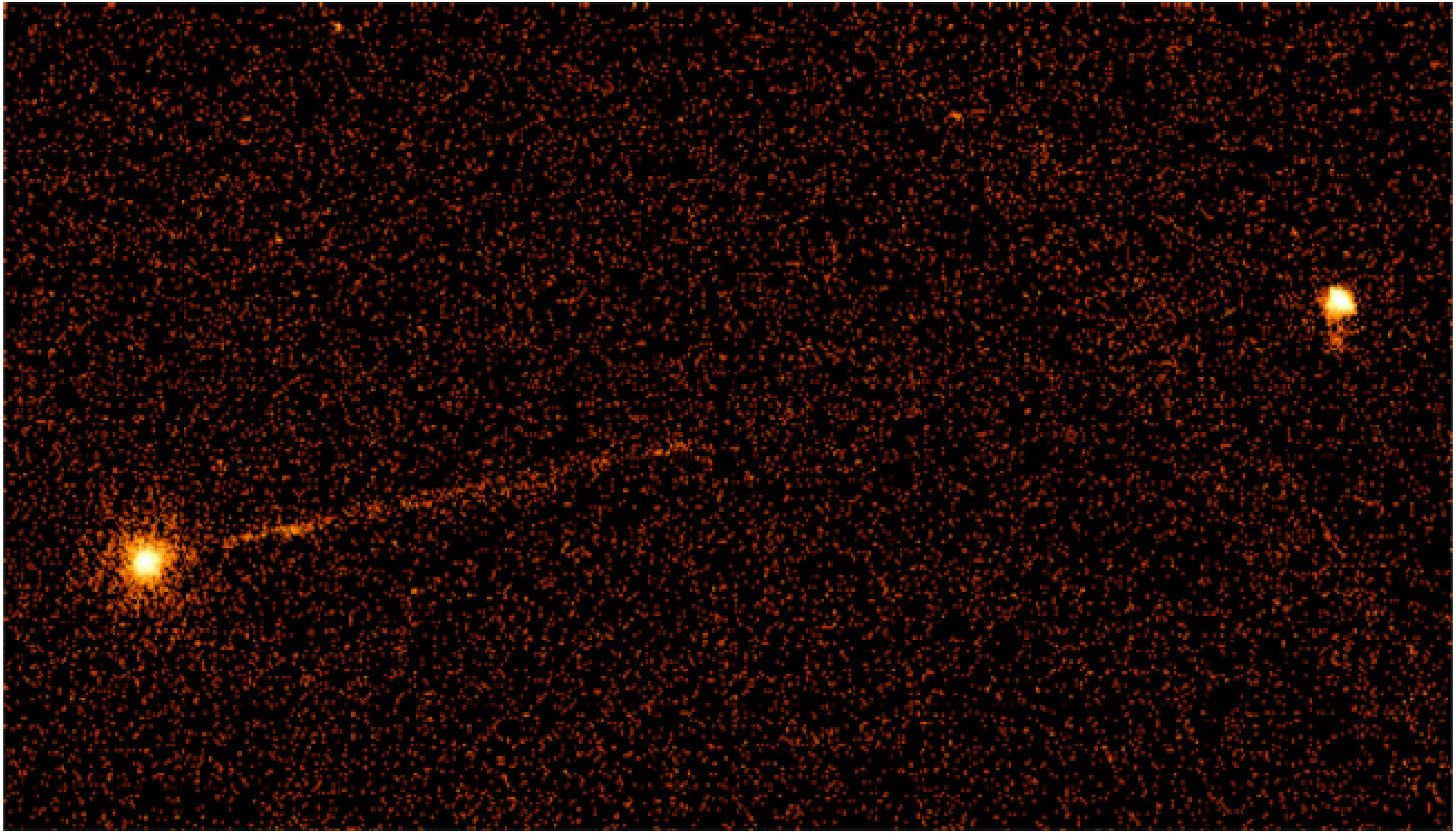
Event	**Display**
Core collapse SNe	Long GRBs\XRFs
Accretion Induced Collapse (SNIa)	(SHBs/GRBs/XRFs?)
Merger of compact binaries (n-n, n-bh)	(SHBs?)
Phase transition in hyperstars(?)/magnetars(?)	SHBs,,SGRs
Microblazars	(XRFs/GRBs ?)

A1987 The two CBs fired by SN

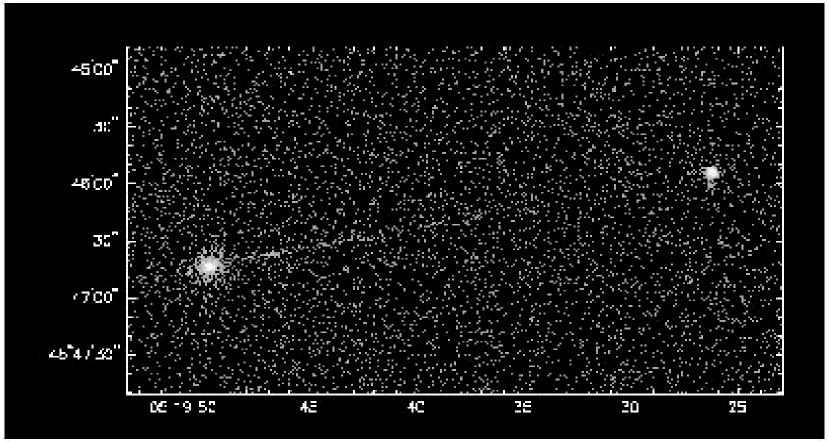
Nisenson & Papaliolios
ApJ 518, L29 (1999)



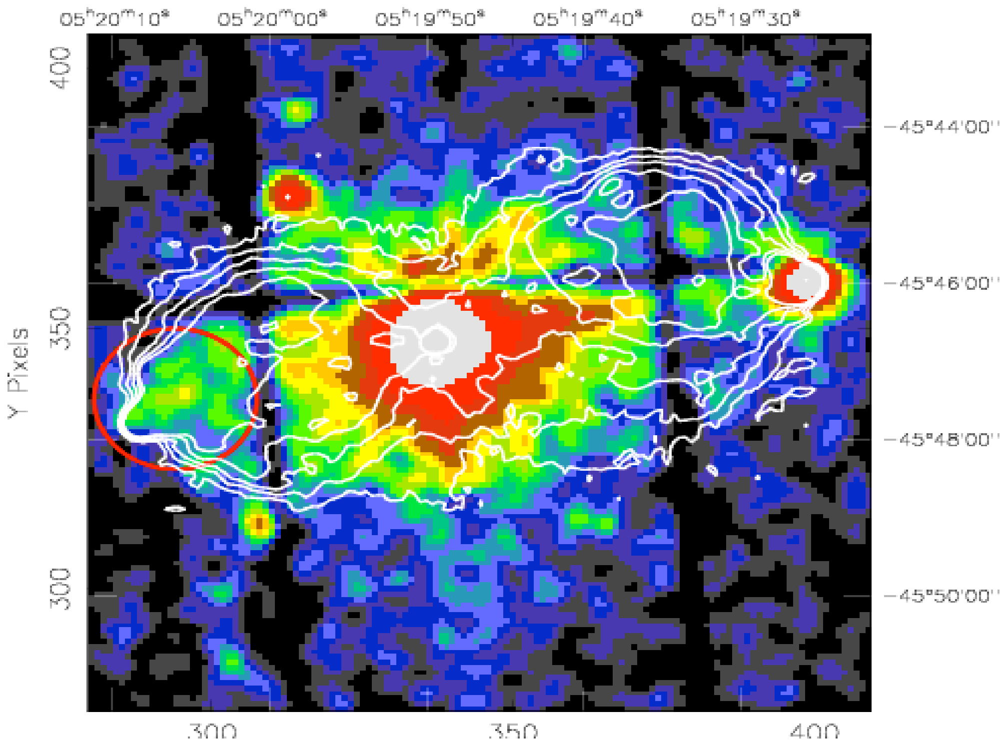
Chandra X-ray image of the quasar Pictor A



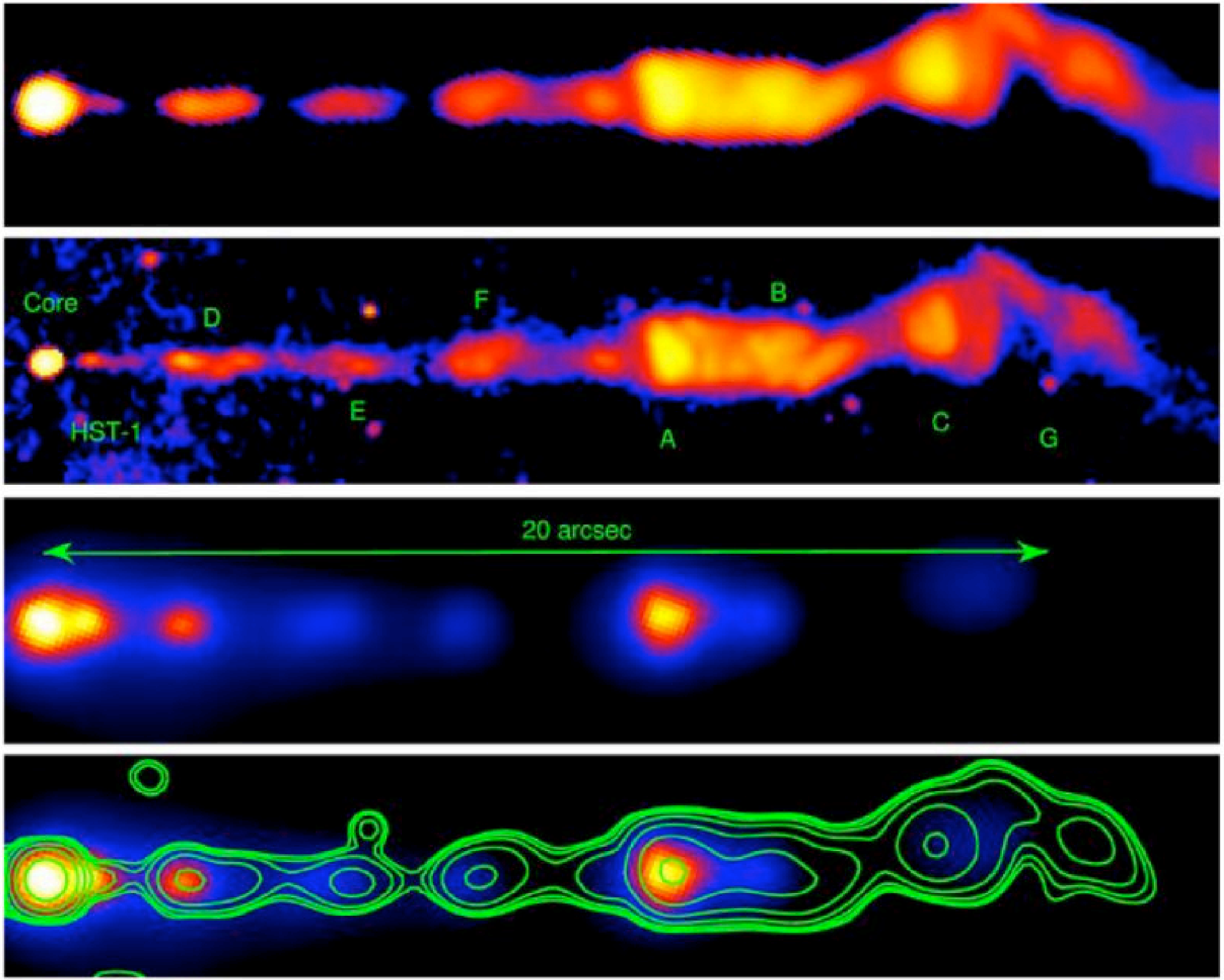
Pictor A
Chandra X-ray image
(Emission from the Jet)



1.4 GHz VLA radio image
(Emission from accelerated CRe’s while diffusing away)



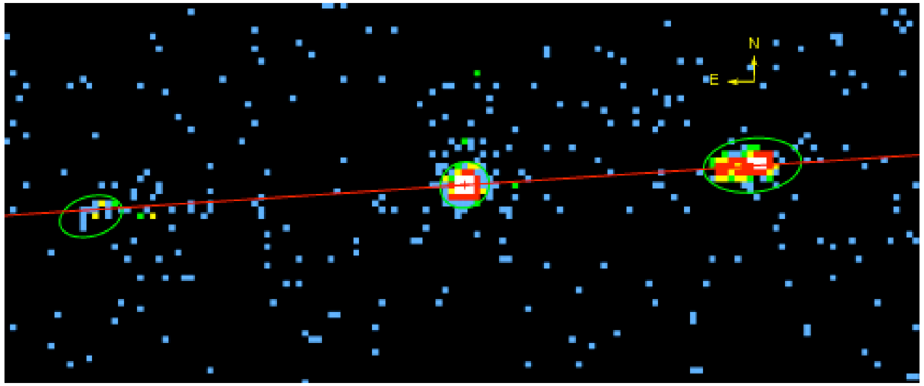
M87: Cosmic Cannon



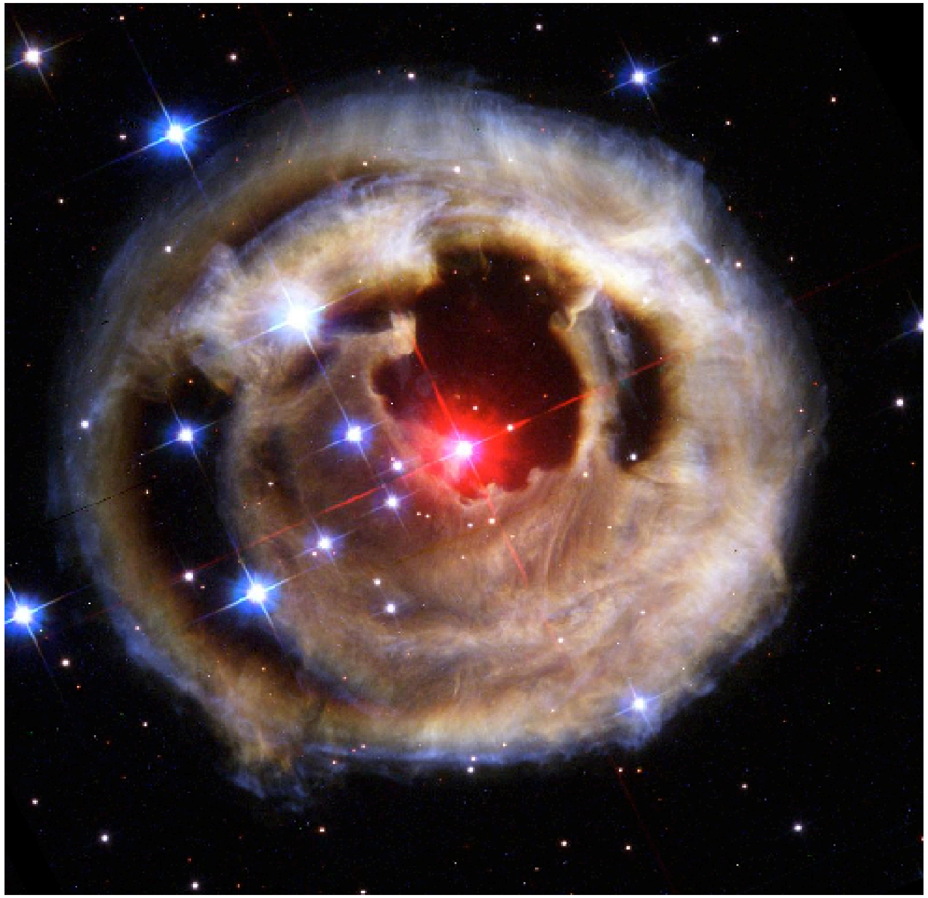
Radio

Optical

X-ray



CBs fired by the microquasar XTE J1550-564 seen in X-rays by Chandra (Corbel et al. 2002)



HST image of the glory (dust echo) of the stellar outburst of the red supergiant V383 Monocerotis on early January 2002 taken on 28 October 2003 (Bond et al 2003)